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Two Dimensional Bistable Vibration Energy Harvester

B. Andò, S. Baglio, F. Maiorca, C. Trigona *

DIEEI, University of Catania, Viale Andrea Doria 6, 95125 Catania, Italy

Abstract

In this paper a new strategy for broadband, bi-directional, vibration energy harvester is presented. Often energy harvesting systems address unidirectional incoming energy, however this is a strong limitation when considering real applications; in fact it is very likely that incoming vibrations will not be aligned with the direction of motion of the harvester. Irregular vibrations along several orientations reduce the energy conversion and the harvester efficiency.
A suitable harvester architecture for collecting energy from vibrations distributed along different directions is needed. Furthermore, often the ambient vibrations come with energy distributed over a wide spectrum of frequencies, with predominance of low frequency components.
This work addresses both these issues by proposing a nonlinear bistable oscillator based on two-dimensional, magnetically-coupled, PZT-based beams able to extract energy from ambient vibrations with arbitrary directions. The basic idea will be presented together with the experimental prototype realized and the results obtained.

Keywords: Nonlinear Energy Harvesting; Bistable Systems; Wideband Vibrations; Piezoelectric Materials;

1. Introduction

The harvesting energy for use in powering has represented the focus of many recent researches [1-3]. Among all the possible energy sources to be harvested, this paper will consider only the ambient vibrations, in fact this represents an ubiquitous source of energy [4] that is also suitable for many different applications [5]. Energy harvesters need a dedicated section for the proper conversion of the energy scavenged into electrical energy [6], here PZT materials will be used as active element to convert the incoming kinetic energy into electrical energy. In order to generate maximum power from energy harvester, a good matching between source and the harvester in terms of vibration directions and

* Corresponding author. Dr Carlo Trigona Tel.: +39(0)95-7382301; fax: +39(0)95-7387945
E-mail address: carlo.trigona@diees.unict.it

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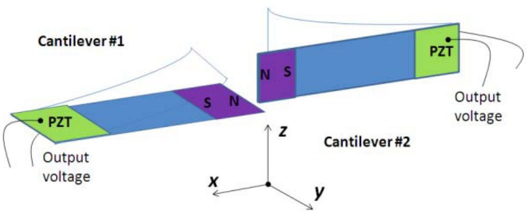
frequencies are needed. Several approaches have been proposed where interesting solutions are investigated to approach both these issues [7]. However often the direction of the vibration is unknown, as a consequence the power efficiency will drastically decrease. At the same time, the ambient vibrations have energy distributed over a wide spectrum of frequencies [8]. Several devices have been proposed in literature having two or three [9] axes vibration and capable to harvest energy; moreover several solutions have been proposed concerning nonlinear approaches to "enlarge" the bandwidth of the harvester [8,10-12].

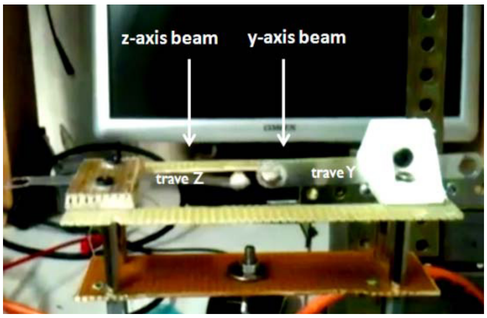
Here we address both these issues proposing a novel two-dimensional nonlinear energy harvester optimized to extract energy from random vibrations. An experimental prototype has been developed, analytic models have been derived and matched with experimental findings. Moreover a data acquisition campaign has been performed in order to show the suitability of the approach proposed.

2. Description of the working principle and of the device prototype

The bi-axial vibration energy harvester proposed in this work is composed of two magnetically coupled bistable beams, with piezo electric output, capable to recovery energy even when the direction of ambient vibration is not aligned with the beam axes. The prototype is shown in the following Fig. 1 together with a drawing that shows the working principle. Two cantilevers are used one that deflects along the **z** direction, the other moving along **y** direction; two NdFeB permanent magnets have been placed on the two cantilever tips with opposite magnetization in order to provide for repulsive force. As stated above, this device (thanks to the combined action of the two orthogonal cantilevers) allows for collecting energy from incoming vibrations in two however oriented on the **y-z** plane. Each cantilever will sense the component of the vibration along its sensing direction, therefore for generic vibrations on the **y-z** plane each one of the two cantilevers will respond to the projection of the kinetic energy along its own axis respectively. All the incoming energy is therefore collected. The presence of permanent magnets on the cantilever tip has been largely exploited by the author in order to obtain bistable behaviors [10-12] and therefore to improve the device performances thanks to the enlargement of the PSD at lower frequencies. The presence of the two opposing magnets allows for obtaining a greater efficiency also for the issue of bi-directional energy harvesting; in fact the vibrations induced in one of the two beams are transmitted to the other cantilever through the magnetic coupling due to the couple of opposite magnets, that are also responsible of the bistable behavior.



(a)



(b)

Fig. 1. (a) Device for bi-axial vibration energy harvesting, a graphical description of the device working principle; (b) picture of the laboratory experimental prototype developed

Therefore each beam behaves bistable whichever is the direction of the incoming vibration thus resulting into a very efficient energy scavenging. The analytical model can be described through two magnetically-coupled second order equations [13] having masses m_i, springs k_i and damping d_i (i=1,2).
The two terms k_{nl} and k_{nlc} represent the nonlinear coupling correlated with each displacement (y and z) and with relative displacement of each cantilever respectively. The term d_m is the magnetic damping effect while the noisily source is represented by n_y an n_z:.

$$\begin{cases} m_1\ddot{y} + d_1\dot{y} + k_1 y - k_{nl}y - k_{nlc}(z-y) - d_m(\dot{z}-\dot{y}) = n_y(t) \\ m_2\ddot{z} + d_2\dot{z} + k_2 z - k_{nl}z + k_{nlc}(z-y) + d_m(\dot{z}-\dot{y}) = n_z(t) \end{cases} \quad (1)$$

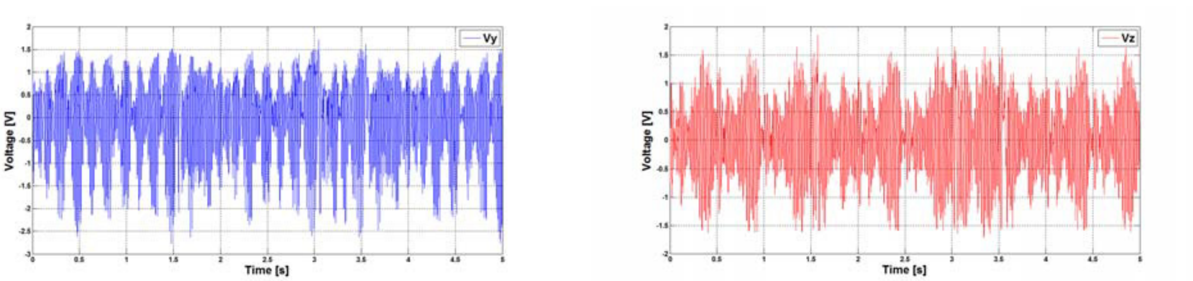
3. Experimental results

The system is composed of two aluminum beams (40mm x 9mm) coupled through two NdFeB permanent magnets both fixed on the cantilever tips and having repulsive force condition in order to create the two stables states.

The experimental setup includes a shaker to impose mechanical vibrations, a band-limited white noise generator to emulate the ambient vibrations (assumed limited at 450Hz), a laser sensor to monitor the mechanical displacement and two piezoceramic elements have been used in order to extract energy from external vibrations. Furthermore an accelerometer has been used as a feedback element.

Fig. 2 and Fig. 3 show some experimental results in the case of vibrations level of about 9g rms are reported. The acceleration is imposed along the **z** direction, it can be observed as the two cantilvers are both vibrating, due to the magnetic coupling.

In particular Fig. 2a and Fig. 2b show the piezoceramic element output for both vibrating system, detecting a variation (pep) of about 4.5V with a resistive load of 330kΩ. The vibrations induced through the shaker in the z-axis beam are transmitted to the y-axis beam (or vice versa) obtaining two bistable behaviors. As consequence a wide spectrum appears thus resulting into a very efficient energy scavenging.



(a) (b)

Fig. 2. PZT output voltage, (a) y-axis beam, (b) z-axis beam. The measures across the resistive load of 330kΩ have been performed by using a differential probe.

4. Conclusions and future trends

The experimental results show the suitability of the system to recovery energy from vibration coming from different directions. A maximum power of about 3.2µW (rms) has been detected for each beam with optimal load of about 330kΩ. An improvement in terms of bandwidth (flat) and power harvested (10-times more) compared with the linear system has been observed. Validation of this principle with SOI-MEMS prototype is in progress.

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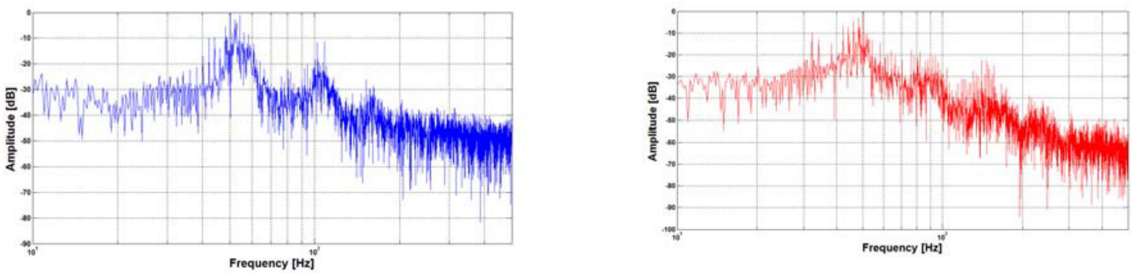

Fig. 3. Voltage spectrum: (a) y-axis beam, (b) z-axis beam.More energy can be collected al low frequency furthermore more energy can be collected from two motion axes.